

The effects of red supergiant mass loss on supernova ejecta and the circumburst medium

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Abstract. Massive stars becoming red supergiants lose a significant amount of their mass during that brief evolutionary phase. They then either explode as a hydrogen-rich supernova (SN Type II), or continue to evolve as a hotter supergiant (before exploding). The slow, dusty ejecta of the red supergiant will be over-run by the hot star wind and/or SN ejecta. I will present estimates of the conditions for this interaction and discuss some of the implications.

1. Red supergiants

At first glance the definition of a red supergiant seems clear-cut: it is a large star with a red colour. The red colour is a result of the photosphere being cool, which in turn is the result of the adjustment of the structure of the stellar mantle to facilitate energy transport (which through a large portion of the mantle happens *via* convection) from the stellar interior where it is produced out to the photosphere. For a cool star to radiate away the energy at the same high rate at which it is produced by nuclear burning, the radiating surface must be enormous, as $L_{\star} = 4\pi R_{\star}^2 \sigma T_{\text{eff}}^4$. The *super* in supergiant refers to the effective gravity being particularly low; the effect of the effective gravity on the shapes of spectral lines forms the basis for the Morgan-Keenan system of luminosity classes. In practice, this often (but not always) translates into a higher luminosity for the red supergiants, which have luminosity class I, than for the *not-so-super* red giants, which have luminosity classes II (high up the Asymptotic Giant Branch) or III (lower on the AGB, or on the first-ascent Red Giant Branch). The specific nuclear burning rate increases with increasing pressure and temperature, and the luminosity further increases with increasing mass (fuel) of the nuclear engine; these all increase in more massive stars, and thus red supergiants are features of the evolution of massive stars. The underlying reasons for the change from a relatively compact main-sequence star to a red supergiant remain elusive — it is not merely due to their huge luminosity, as the evolution of massive stars towards (and away from) the red supergiant phase is accompanied by relatively little change in luminosity.

At second glance, it is not obvious at what point a star can be called a red supergiant. How cool must it be? Stars with spectral types similar to that of the Sun, but luminosity class I are called yellow supergiants, or yellow hypergiants to distinguish them from the luminosity class II post-AGB stars. Very luminous K-type giants could be called orange supergiants. It seems logical to define red supergiants as those stars of luminosity class I and an M-type spectrum. This

turns out to be a very useful criterion, as the M class is characterised by the appearance of additional molecular absorption bands in the optical spectrum, and this is accompanied (if not followed) by other important phenomena such as radial pulsation and circumstellar dust. The other criterion, the luminosity class, is complicated by the fact that at the lower end of the mass spectrum of red supergiant progenitors, red supergiants are not necessarily more luminous than stars at the tip of their AGB, descendant from relatively massive intermediate-mass stars. If this is not enough, these red supergiants are also warmer and thus smaller than their AGB luminosity-equivalents; and the most extreme AGB stars will have reduced their mass to close of that of a white dwarf (which will have further contributed to their increase in size and reduction in photospheric temperature), while red supergiants may still carry a significant fraction of their birth mass. Consequently, the effective gravity of a red supergiant can be much higher than that of a red giant.

For the purpose of this discourse, and as a suggestion for a meaningful use of the term, we introduce here a hybrid definition of red supergiant, marrying an observational with a theoretical criterion: *a red supergiant is a massive star with spectral type M*. Note that we have not yet specified what we mean by massive.

1.1. The nature of red supergiant progenitors and descendants

So which stars make it to the red supergiant phase? Often, a lower birth mass of $M_{\text{birth}} > 8 M_{\odot}$ is adopted for stars that upon exhaustion of helium-burning, and contrary to AGB stars, proceed to ignite carbon in their cores. But this relies on the treatment of convection and other types of mixing in the core and circum-core regions, and can be as low as 5–6 M_{\odot} in models with efficient convective overshoot (the ability of convection cells to penetrate regions that are formally stable against convection, due to inertia). The stars that straddle the distinction between entrance into the red supergiant phase or termination on the AGB have ages of around 40 Myr. This is a few times longer than typical lifetimes of molecular clouds, and at a modest peculiar velocity of 1 km s⁻¹ the star would have wandered off by 40 pc anyhow; red supergiants (and their immediate progenitors) can thus be encountered well outside H II regions.

Stars too massive do not become red supergiants. They terminate their evolution prematurely, as Wolf-Rayet stars with helium-rich photospheres, or as Luminous Blue Variables hitting the S Dor instability strip (or the Humphreys-Davidson Eddington-luminosity limit in the case of the most massive stars). The transition regime between stars that do become red supergiants and those that do not, occupies approximately the $M_{\text{birth}} = 25\text{--}30 M_{\odot}$ range. However, it appears to depend on details that may differ between stars of the same birth mass: the overall metallicity of a star affects the opacity profile throughout the stellar mantle, and thus its structure; rotation could lead to extra mixing of nucleosynthesis products throughout the stellar interior, thereby facilitating transformation into a red supergiant; mass loss in the preceding stages also affects the prospects for a star to become a red supergiant, and this likely depends on metallicity and angular momentum. The upper mass limit to red supergiant progenitors is difficult to determine observationally, as massive stars are under-represented in co-eval stellar aggregates and the red supergiant evolutionary

phase is particularly brief. But the absence of evidence for red supergiants younger than ~ 10 Myr supports the afore-mentioned mass cut-off.

Red supergiants have reduced mass, compared to their birth mass. During their lives on the main sequence, but more importantly — especially for the lower-mass stars — during the post-main sequence phase as blue, B-type supergiants, the progenitors of red supergiants lose mass through a wind driven by radiation pressure mainly in the UV transitions of metallic ions. The mass-loss rates typically reach values of $\dot{M}_{\text{blue}} \sim \text{few} \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. In this manner, a few M_{\odot} may be lost prior to the red supergiant phase. The mass-loss rate can not be computed *ab initio*, and direct measurements may have been over-estimated by up to an order of magnitude because of the unknown degree of clumping in the wind. The subsequent migration across the A–K spectral types is rapid, and mass loss then thus seems of limited importance. However, LBVs are seen also at relatively-low luminosity; in fact the S Dor instability strip appears to span across the Hertzsprung-Russell diagram, from the most massive blue hypergiants down towards, and intersecting if extra-polated, the AGB. Stars evolving from the main-sequence towards the red supergiant phase inevitably cross this strip. What determines the instability — and thus the symptoms these stars develop — is unclear. It is also unclear how much additional mass is shed during the LBV phase (or cycles). There thus remains a possibility that red supergiants can have mantles of very little mass. This is important, as this would facilitate the transformation of red supergiants into Wolf-Rayet stars due to the drastic reduction in mantle mass (and thus the inwards migration of the photosphere) resulting from mass loss during the red supergiant phase.

For reasons yet unclear, less massive red supergiants may undertake an excursion towards hotter photospheric temperatures, possibly to return to enter the red supergiant phase for a second time. These blue loops resemble in some respects the horizontal-branch phase that metal-poor low-mass stars experience in between the RGB and AGB phases. In conclusion, red supergiants may have had a very rich and complicated live indeed, and likewise hot supergiants may have gone through a red supergiant phase some time in their recent past.

1.2. Supernovae with red supergiant progenitors

Red supergiants are the classical, predicted progenitors of core-collapse supernovae. Upon helium exhaustion, the star will proceed rapidly through subsequent successive stages of nuclear fusion until it no longer is an exothermic process, the core will collapse under its own gravity until halted by neutron pressure, the inner mantle will bounce off the newly formed neutron star, and the resulting shock wave will traverse the outer mantle which had hitherto been unaware of the dramatic events unfolding inside. Thus a hydrogen-rich (Type II) supernova event occurs. If the red supergiant transformed into a Wolf-Rayet star before exploding, the supernova would be of a hydrogen-poor type, Type Ib or c (Type Ia is usually linked with white dwarves). If a black hole formed instead of a neutron star, which might be the case in massive red supergiants, then the shock wave is likely to be much weaker (in the absence of a solid surface to bounce off) and thus the supernova fainter, and possibly the ejecta would be smaller in mass. On the other hand, the relatively light mantles of the least massive red supergiants might be entirely shed during their relatively

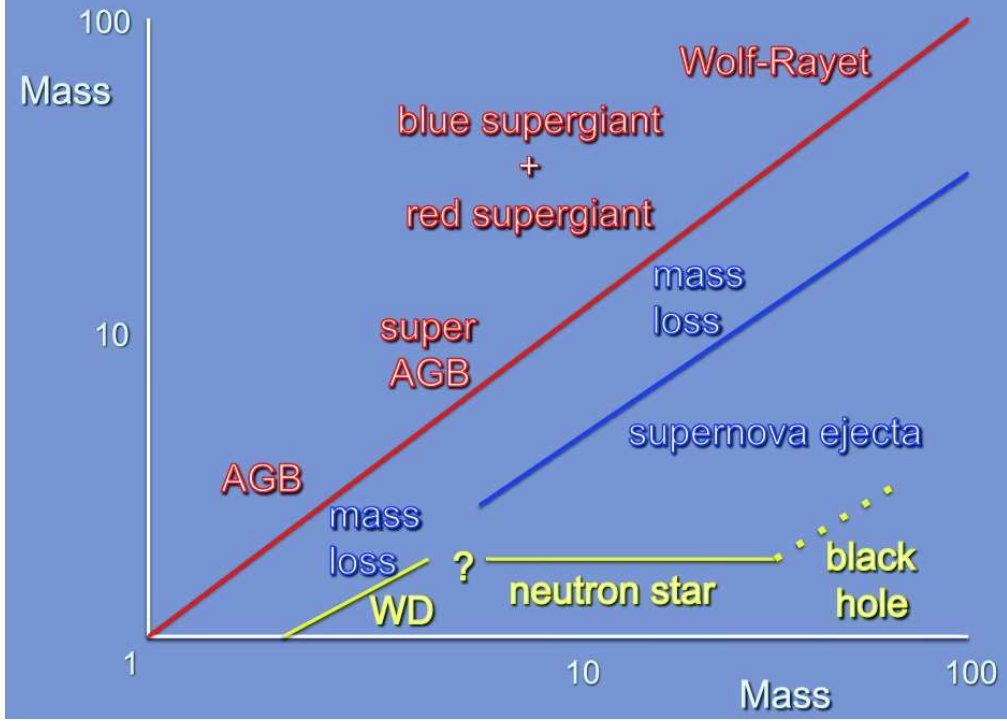


Figure 1. Schematic context for red supergiant evolution and their mass loss.

long-lasting red supergiant phase. Like other red supergiants, these stars go on to burn carbon in their cores, but like AGB stars they experience thermal pulses as different shells burn alternately. These so-called super-AGB stars might terminate their evolution prematurely, leaving behind an oxygen-neon white dwarf; however, if the mass loss is insufficient they will proceed to the next stage, and in their case electron capture will cause a fall in pressure which induces a supernova event, probably of Type II. Figure 1 presents a schematic overview — the boundaries in mass between the various scenarios, and between the mass lost through pre-supernova mass loss and supernova ejecta, are all rather insecure.

Red supergiants have recently been confirmed directly to be associated with supernovae of Type II-P (Smartt et al. 2009). These supernovae have lightcurves characterised by a plateau phase (hence the P sub-type); which is when the ejecta have large opacity due to their ionisation by the shock wave, causing the storage of photons within the expanding ejecta until the ejecta recombine, the opacity drops, and the photons escape freely. Clearly, these red supergiants were some way from shedding their mantle through (more gentle) mass loss. The masses of these red supergiant supernova progenitors span a range in mass of $M_{\text{birth}} = 8.5\text{--}16.5 M_{\odot}$ (Smartt et al. 2009). This leaves little room for super-AGB stars to yield a markedly different type of supernova from their more massive siblings. It has been suggested that the core collapse in the most massive red supergiants, in the mass range of 17–25 (or higher) M_{\odot} , might result in black holes and possibly lead to faint events of Type II-L (with optically thin ejecta causing a linear decay in the lightcurve, lacking the plateau).

2. Red supergiant mass loss

2.1. Characteristics of red supergiant winds

In his seminal paper on the discovery of a wind emanating from the M5-type red supergiant α Herculis, the massive component of a visual binary, Armin Deutsch (1956) laid the foundations for what we know about red supergiant mass loss. The optical, violet-displaced absorption lines were used to infer a wind speed of $v_{\text{wind}} \sim 10 \text{ km s}^{-1}$, and a mass-loss rate of at least $\dot{M} > 3 \times 10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$. He also pointed out that the line broadening in the photospheres of red supergiants suggests turbulent motions at the level of a few km s^{-1} . One might expect such turbulence to persist through at least the inner regions of the outflow. He also noted the irregular variability of the light output from the star; the associated radial motions at the base of the atmosphere also reach a few km s^{-1} . Thus, the slow winds from cool supergiants are not expected to be homogeneous. Indeed, Deutsch inferred a clumpy medium, with electron densities $n_e \sim 10^6 \text{ cm}^{-3}$ inside clumps and a volume filling factor of only $1:10^7$. Deutsch realised that this wind is unlikely to be a peculiarity of α Herculis, and that in fact mass loss must be commonplace among all M-type giants and supergiants.

In 1971, Gehrz & Woolf published another seminal paper, on a sample of M-type giants and supergiants including α Herculis: they found that the winds of these stars are dusty, causing extra emission at mid-IR wavelengths at the expense of optical light. Adopting a density profile and a gas:dust mass ratio assuming all silicon were in solid form, they derived a mass-loss rate for α Herculis of $\dot{M} \sim 9 \times 10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$, in fantastic agreement with the estimate by Deutsch. They realised that these estimates should be regarded as lower limits, as the dust condensation process may not be 100% complete.

How typical is α Herculis? Gehrz & Woolf (1971) estimated much higher rates of mass loss for most other red supergiants, up to $\dot{M} \sim 10^{-5} \text{ M}_{\odot} \text{ yr}^{-1}$; in fact, the rates from the dustiest-known red supergiants — *e.g.*, VY Canis Majoris and NML Cygni — reach values of $\dot{M} \sim 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$ (Jura & Kleinmann 1990). Wind speeds of red supergiants are also higher in general than that in α Herculis, typically $v_{\text{wind}} \sim 20\text{--}30 \text{ km s}^{-1}$ in the Milky Way (*c.f.* Jura & Kleinmann 1990). The mass-loss rates do not appear to depend on the metallicity at birth, but the dust:gas mass ratio, ψ scales in direct proportion to metallicity and the wind speed scales as $v_{\text{wind}} \propto \psi^{0.5}$ (Marshall et al. 2004; van Loon et al. 2005, 2008). In the Milky Way, $\psi \sim 1:200$ in relatively dusty stars.

The density in the wind, $\rho = \dot{M}/(4\pi r^2 v_{\text{wind}})$ spans a vast range: near the base of the wind, at $r_{\text{in}} \sim 10^9 \text{ km}$ (several AU), the density can exceed $\rho \sim 10^{-15} \text{ g cm}^{-3}$ (assuming $\dot{M} \sim 10^{-5} \text{ M}_{\odot} \text{ yr}^{-1}$), or $n \sim 10^{12} \text{ particles cm}^{-3}$. Assuming the wind was maintained for a period of 10^5 yr , the earliest ejecta could possibly have reached a distance of $r_{\text{out}} \sim 10^{14} \text{ km}$ (a few pc); by then, the density would have dropped to $n \sim 100 \text{ particles cm}^{-3}$, or $n \sim 1 \text{ particles cm}^{-3}$ for a more moderate mass-loss rate of $\dot{M} \sim 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$. This approaches the density of the diffuse interstellar medium in the Galactic Disc. The wind cools, *via* emission by grains, molecules and atomic fine-structure lines, and the temperature in the outer regions of the wind will reach a balance set by the local interstellar radiation field, typically a few dozen K. With $P_{\text{out}} = nkT \sim 10^{-20}$ to 10^{-18} bar , the internal pressure of the outer wind may thus not be too different

from that of the interstellar medium. The ram pressure exerted by the bulk flow, $P_{\text{ram}} = \rho v^2 \sim 10^{-17}$ to 10^{-15} bar, *i.e.* a thousand times higher than the internal pressure. Close to the star, the wind temperature can be $T_{\text{in}} \sim 1000$ K and the internal pressure can be more comparable to the ram pressure, especially in the relatively-slow winds of metal-poor red supergiants.

2.2. The red supergiant mass-loss mechanism

Deutsch (in his 1956 paper) realised that the wind speed in α Herculis is much lower than the escape velocity from the stellar photosphere, $v_{\text{esc}} \sim 100 \text{ km s}^{-1}$. He assessed the possibility that radiation pressure on the circumstellar ions (and atoms) could drive the wind until the local escape velocity would have dropped below the wind speed, but the values for the achieved acceleration he computed fell short by orders of magnitude and thus he invoked an as yet unidentified mechanism. Gehrz & Woolf (in their 1971 paper) demonstrated that radiation pressure on dust grains, which have large continuum opacity (thus easily building a large optical depth, τ) at optical wavelengths, may be sufficient to drive the wind. Even though the grains form a minority compound, collisions between grains and gas particles in the dense inner parts of the winds are frequently enough for the gas to be dragged along with the grains, and the luminosity of red supergiants is sufficiently high to provide the required radiation pressure, $P_{\text{rad}} = \tau(L/c)/(4\pi r^2)$, at least until both fluids are gravitationally unbound from the star (see, *e.g.*, Ferrarotti & Gail 2006). The dust-driven wind paradigm predicts a dependence of the wind speed on the luminosity, $v_{\text{wind}} \propto L^{0.25}$ (approximately), which has been confirmed observationally by measurements of OH 1612 MHz masers in the Large Magellanic Cloud and the Galactic Centre (Marshall et al. 2004). The maximum mass-loss rate attained by red giants and red supergiants appears also to increase with increasing luminosity (van Loon et al. 1999), as well as with decreasing temperature of the stellar photosphere (van Loon et al. 2005). However, to take this, too, as evidence for a radiation-driven outflow would be misleading as the paradigm does not, in fact, explain how the wind is initiated, in the dust-free atmosphere closest to the star. The density at the critical point, at which acceleration by radiation pressure starts operating, is set by an alternative mechanism.

The presence of a dusty wind goes hand-in-hand with radial pulsation of the stellar photosphere. Even though the bolometric amplitude of red supergiants rarely exceeds a few tenths of a magnitude, compared to a magnitude for dusty AGB red giants, in terms of absolute units of energy the pulsation of red supergiants is at least as powerful as that in AGB stars, and a good correlation is observed between the mass-loss rate and the energy involved in the pulsation cycle (van Loon et al. 2008). However, the energy involved in the outflow is several orders of magnitude less than that in the pulsation, and one can not therefore assume that the pulsation directly (mechanically) drives the mass loss. That said, radial pulsation has two important effects: it leads to a sustained increase in the scale-height of the atmosphere, and the associated shocks accommodate the condensation of gas onto nucleation seeds and further grain growth (Bowen 1988). Relatively-warm red supergiants (of early-M type) do not always pulsate very strongly, nor possess as much dust as expected, *e.g.*, Betelgeuse (van Loon et al. 2005; see also the contribution by Graham Harper).

These stars bear the signature of a chromospheric temperature-inversion layer; although gas pressure alone is not thought to be sufficient to drive a Parker-type wind, the magneto-acoustic waves that are at the origin of heating the chromosphere might dissipate in the right manner to drive mass loss. The transitions between chromospheric and pulsation-driven regimes of mass loss, and the associated phase change in the thermodynamic and compositional state of the wind, are mapped beautifully for lower-mass red giants by Judge & Stencel (1991), McDonald & van Loon (2007), and McDonald et al. (2009).

2.3. Complications with empirical mass-loss determinations

One must realise the current limitations on theoretical and empirical values and formulae for the mass-loss rates of red supergiants. As for theory: no *ab initio* models exist that reliably predict mass-loss rates. Measurements of mass-loss rates derived from the effects of dust on the spectral energy distribution (which yields a value for τ) rely on knowledge of the dust:gas mass ratio, wind speed, and luminosity (hence distance), parameters which are rarely known accurately. Measurements of mass-loss rates derived from molecular line emission at micro-wavelengths suffer from uncertainties in envelope chemistry and again distance, apart from detecting these lines being more challenging than detecting dust emission. As already noted by Deutsch (1956), measurements of mass-loss rates from optical absorption line profiles suffer from uncertainties in the ionization profile throughout the envelope, as well as the degree of clumping, and from the fact that they may not trace (only) the mass which eventually escapes. Furthermore, winds of red supergiants, in particular (or perhaps more easily noticed) the dustiest ones, are rarely spherically symmetric — see, *e.g.*, the spectacular resolution of the circumstellar dust envelope surrounding an extragalactic red supergiant by Ohnaka et al. (2008). Also, the mass-loss rate of any given star will have varied in the past, and depending on the method employed a rate will be obtained which refers to a certain moment in the past (or an average rate, possibly weighted over time in a complicated manner) — even the freshest dust was formed from material which left the stellar photosphere a few years earlier, and cold dust and molecular line emission may trace mass loss $> 10^4$ yr in the past. Correlating these rates with the current stellar properties may thus be physically inappropriate. To summarise, individual mass-loss rates of red supergiants are at least a factor two or so uncertain, but they can be in error by more than an order of magnitude. Some of the uncertainty may be systematic within a given sample of stars, which affects the derivation of empirical formulae.

3. Red supergiant mass loss in evolutionary context

3.1. Dependence on the preceding evolutionary phase

There are two important dependences of red supergiant mass loss on what has happened before, the first being the structure of the red supergiant mantle, or: how cool does the photosphere become? This is of crucial importance, as the mass-loss rate is observed to be higher at a lower temperature (§2.2); this is probably related to the fact that cooler red supergiants have more tenuous mantles (a million times less dense than their main-sequence mantles!) which

are inherently unstable against fundamental-mode radial pulsation. Indeed, the closer a star approaches the Hayashi boundary, the closer it is to hydrostatic imbalance. The intricacies of pre-red supergiant evolution are more adequately described elsewhere, but we note that, for example, rotation enhances mixing, causing enhancement of carbon, oxygen, and in particular nitrogen, throughout the mantle (Meynet, Ekström & Maeder 2006). This, in turn, lowers the photospheric temperature of the red supergiant. It was suggested that this would also lead to enhanced mass loss, but if it does then it is more likely to be related to the more unstable mantle, rather than to enhanced dust formation as a result of a larger amount of refractory elements: dust *condensation* — in particular in the oxygen-rich environments of red supergiants — is probably limited by the abundance of nucleation seeds, which rely on elements such as titanium, and, with the dominant oxygen-rich grain material being silicates, grain *growth* will be limited by the availability of silicon (van Loon et al. 2008). Neither titanium nor silicon are enhanced.

Mass loss itself also affects the structure of the mantle. Approximating the star as a polytrope, the radius of the star will grow as the mass is reduced, $R \propto M^{-1/3}$. This, in turn, will cool the photosphere (as the luminosity remains largely unaffected) and possibly enhance the mass loss. Besides the cooling effect, the growing radius and shrinking mass both lead to a reduction of the surface gravity of the star; mass-loss rates of red giants are known to show a clear anti-correlation with surface gravity (Judge & Stencel 1991; McDonald et al. 2009). It is not understood what would prevent this from becoming a runaway process — perhaps this causes the final ejection of a proto-planetary nebula by an AGB star, but a similar sudden shell-ejection is not known to occur in red supergiants. The effect of a larger radius would also be noticed in the length of the pulsation period, which is relatively straightforward to measure (and which does not depend on distance), as for a harmonic oscillator, $P \propto R^3$. Hence, $P \propto M^{-1}$. As the luminosity is a reflection of the birth mass, the difference between the luminous mass and the pulsational mass, $\Delta M \equiv M_{\text{lum}} - M_{\text{puls}}$ measures the time-integrated mass loss. This would be worthwhile to attempt in the recently-discovered massive, young Galactic clusters; these harbour more than a dozen red supergiants each (see Ben Davies’ chapter in this book), thus each presenting a series of snapshots out of the movie telling the life-story of a star. This can then be tied in with direct measurements of the mass-loss rates along these cluster red supergiant sequences.

The second dependence is that of the circumstellar environment. All red supergiants were once blue supergiants (§1.1). Much speedier, $v_{\text{wind}} \sim 10^3 \text{ km s}^{-1}$, winds of blue supergiants exert vastly higher ram pressure on the surrounding medium than the winds of red supergiants. On the other hand, the fast wind would have quickly swept-up an equivalent amount of interstellar matter and thus slowed-down significantly merely for reason of conservation of momentum: this happens already within a century — $t = (3\dot{M})^{0.5} (4\pi\rho_{\text{ism}})^{-0.5} v_{\text{wind}}^{-1.5}$. Also, the energetic radiation from the B-type star creates a Strömgren zone of warm plasma, the internal pressure of which acts as a buffer against expansion of the wind bubble. Before long, the wind bubble will not expand much faster than a km s^{-1} . That said, the subsequent slow, dense red supergiant wind will, at least initially, expand into a rarefied, and quickly-recombined, circumstellar environment; this may alleviate the potential challenges for such a wind to plough into

a molecular cloud, for instance, and justify the normally assumed density profile throughout the (outer) circumstellar envelope of red supergiants, $\rho \propto r^{-2}$.

We must emphasize that mass lost in earlier phases *will* have an impact on the properties of the red supergiant. This previous mass loss may be modest, perhaps only amounting to a few per cent of the birth mass. However, it is an uncertain quantity, and could be underestimated if significant amounts of mass are lost in brief (and thus rarely witnessed) events such as LBV-like eruptions.

3.2. Implications of red supergiant mass loss

Given the uncertainties in mass-loss rates and empirically-derived lifetimes, the mass lost over the entire red supergiant phase, $\Delta M = \int \dot{M} dt$ is uncertain by an amount which is comparable to the mantle mass. Red supergiants lose mass at a rate that is normally not higher than the rate at which nuclear fuel is burnt, meaning that the star will enter the next phase of evolution before having shed the entire mantle; however, during periods of the most intense mass loss, at rates $\dot{M} \sim 10^{-4} M_{\odot} \text{ yr}^{-1}$, the mass loss greatly exceeds the nuclear consumption (van Loon et al. 1999). The exact duration of that extreme phase is thus of crucial importance; it definitely is brief, for few such examples are seen, yet for that reason it is also difficult to estimate precisely. Furthermore, the red supergiant lifetime may be extended by efficient mixing, for instance as a result of rotation (Meynet et al. 2006); this means that the integrated mass loss may differ between stars of the same birth mass (and even of the same initial metallicity), further complicating theoretical predictions as well as their empirical tests.

Although red supergiants with birth masses $< 17 M_{\odot}$ are seen to explode before having had time to shed their hydrogen-rich mantles, the fate of more massive red supergiants is a mystery. At the top end, it is unclear whether red supergiants in the approximate birth-mass range of 25–30 M_{\odot} deplete their mantles enough to transform themselves into Wolf-Rayet stars. Although it is difficult to establish direct links between Wolf-Rayet stars and their red supergiant counterparts, the recently-determined, high, empirical mass-loss rate estimates of red supergiants appear to be consistent with the observed Wolf-Rayet star populations (Vanbeveren, Van Bever & Belkus 2007). Post-red supergiant yellow hypergiants are extremely rare, though, but examples have been suggested, *e.g.*, IRC+10 420 (Kastner & Weintraub 1995). At the bottom end of the mass scale, it is unclear whether super-AGB stars shed their mantles to leave an oxygen-neon white dwarf or whether they die prematurely; examples of each have been suggested, *e.g.*, by Williams, Bolte & Köster (2009) and Botticella et al. (2009), respectively. As their luminosities and temperatures do not differ very much from those of the most massive AGB stars, which do shed their mantles in time, it is indeed possible that super-AGB stars may avoid explosion, too; on the other hand, due to their different internal structure their atmospheres may not become as loosely bound as those of AGB stars and thus their mass-loss rates may not reach the same extreme values.

The slow, dense outflow from the red supergiant will be the stage for the next act, be it the faster wind from a hotter star or the very fast blast wave and ejecta from a supernova. A faster outflow will interact with the red supergiant envelope, much as is believed to happen in planetary nebulae around post-AGB objects. Equatorial density enhancements and faster bipolar outflows are a

common feature observed in red supergiants, for instance in their maser profiles or imaged directly *via* their dust emission (*e.g.*, Ohnaka et al. 2008). It is possible, therefore, that features such as the ring observed in the SN1987A aftermath have their origin in the red supergiant phase. Both blue-loop stars and post-red supergiant Wolf-Rayet stars (if they exist) also develop a fast wind, running into a red supergiant envelope; hence it may be possible to distinguish these post-red supergiant objects from stars with similar spectral type evolving directly off of the main sequence, on the basis of their circumstellar geometry — at least in a statistical sense.

Finally, the relative amounts of mass in the envelope and mantle at the time of explosion have a bearing on the amount of dust produced by red supergiants (in the envelope, although this might be destroyed by the forward shock of the supernova) and supernovae (in the reverse shock running through the ejected mantle, although the dust-producing layers underly the hydrogen-rich mantle). The mantle affects the explosive nucleosynthesis and mixing of its products, as well as the luminosity and lightcurve of the supernova; the envelope creates a light echo as it scatters the supernova’s light, besides showing up in the spectroscopic evolution of the supernova afterglow. These dependences need yet to be quantified in reliable detail, but they show huge potential to turn supernovae into probes of the red supergiant mass loss.

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